ABSTRACT

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Telemedicine is much more than just teleconferencing. ISDN could be used in some low-end applications, but many telemedicine applications will require the higher bandwidth and guaranteed qualities of service supported by ATM.

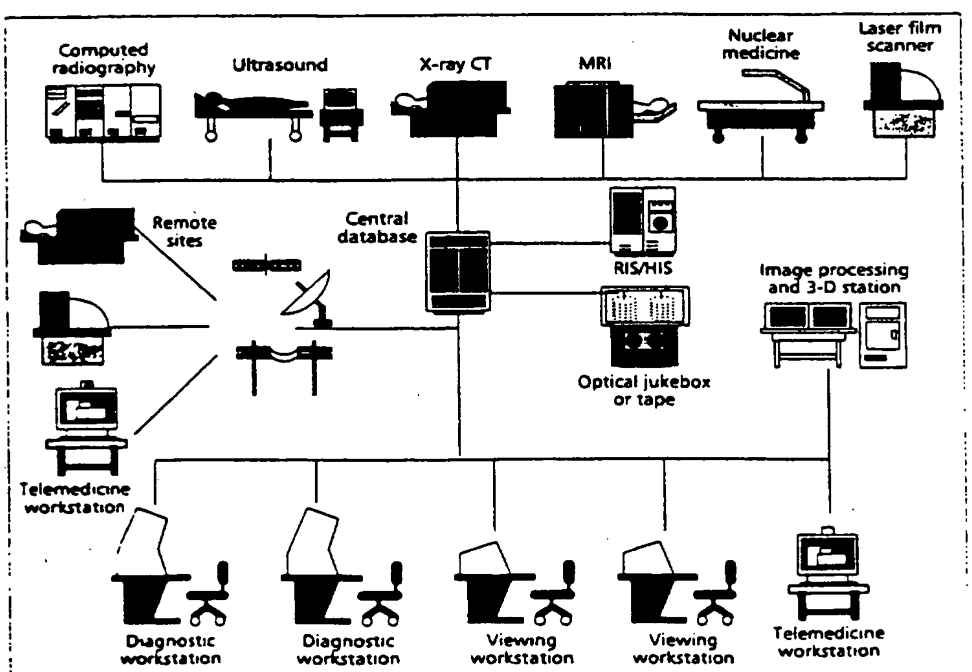
Multimedia Systems for Telemedicine and Their Communications Requirements

James E. Cabral Jr. and Yongmin Kim

Image Computing Systems Laboratory, University of Washington

Telemedicine can be defined as the provision of health care through a combination of telecommunications and multimedia technologies with medical expertise. Telemedicine has become increasingly possible due to a confluence of ongoing technical advances in multimedia, imaging, computers, and information systems as well as in telecommunications. Multimedia systems are now being designed which integrate these technologies to unlock some of the untapped potential in diverse applications. For instance, although many medical imaging devices produce digital images, it has been generally impractical to transmit or access these images interactively over wide area networks. However, the use of compression hardware and software, the widespread acceptance of a medical imaging standard, and the greater available bandwidth in new telemedicine and medical imaging systems make interactive access to these images a reality. Although the cost effectiveness of telemedicine has yet to be proven, and there are other unresolved technical and nontechnical issues, several dozen pilot telemedicine programs are currently being carried out around the world [1]. Once these issues are addressed and solved satisfactorily, many health care providers will be compelled to implement telemedicine systems in order to meet clinical demands and to remain technically current and competitive in an increasingly global market.

The goals of telemedicine are to improve access to care and medical education and to enhance overall quality of care at affordable cost. Improved access to care and cost savings could be achieved by allowing a doctor to remotely examine patients or to consult with a specialist. This reduces or eliminates the time and expense of travel necessary to bring the patient to the doctor or the doctor to the patient [2]. Quality of care is improved by providing the needed services in a timely fashion and expanding the pool of medical specialists available to a given facility, making it more likely that a given case could be handled by an expert if necessary.



■ Figure 1. *An example of using telemedicine to extend a PACS to remote sites.*

Telemedicine has been used since 1959 when early experimenters demonstrated telepsychiatry [3] and telefluoroscopy [4], and new surgical procedures were first broadcast live at national medical conferences. In the 1970s and 1980s, telemedicine experiments focused on the transmission of medical images using television. In the last five years, most telemedicine trials have experimented with the use of videoconferencing for remote consultation. However, none of these early programs has proven to be financially self-sustaining [5].

There are quite a few obstacles to be overcome before telemedicine can be widely deployed. Currently, doctors are required to obtain licenses in each state in which they plan to practice medicine and see patients. Fur-

thermore, legal precedence for remote liability has not yet been established. Reimbursement policies are also not well defined. Teleradiology studies are the only telemedicine sessions that regularly receive reimbursement [6].

Another major obstacle to telemedicine is the scarcity of high-bandwidth telecommunications networks in rural areas, which remains a significant problem even as telecommunications networks nationwide are upgraded to support the national information infrastructure (NII). In addition, the initial costs of equipment and the recurring expenses of telecommunications services are considerable. However, recent acceptance and deployment of picture archiving and communications systems (PACS) [7] in hospitals and the DICOM medical imaging standard can provide an infrastructure to facilitate the implementation of telemedicine systems.

Traditionally, almost all medical images have been printed on radiological film. This film is expensive to produce and easy to misplace, and usually only one copy exists, thus limiting the number of persons who have simultaneous access to the images. Over the last four years, large image management and communications systems or PACS, such as the Medical Diagnostic Imaging Support (MDIS) [8] system developed for the U. S. Department of Defense, have been implemented to reduce or eliminate the need for film. PACSs receive digital images from various imaging modalities in the hospital and store and archive them in a central location from which these images can be downloaded to any client workstation for display across a local or wide area network. This eliminates the hassle and cost of lost film. Also, it supports viewing the images at multiple workstations simultaneously, and allows the clinician to manipulate the images digitally (such as zooming or adjusting the brightness and contrast of the image). In cases where filmless systems are not yet available or migration from existing film libraries to the PACS is necessary, a laser digitizer or high-quality charge coupled device (CCD) camera is used to digitize the films. The availability of medical images via PACS is an important building block of telemedicine. Figure 1 illustrates the extension of a PACS to remote sites using telemedicine.

The Digital Imaging and Communications in Medicine (DICOM) standard [9] has been under development since 1983 by the American College of Radiology (ACR) and the National Electrical Manufacturers Association (NEMA) to tackle the long-standing problem of incompatibility in medical imaging and to provide a standard for interconnection of medical imaging devices on standard networks. Most significantly, the current version 3.0 of DICOM provides a group of standard formats which can be used to exchange images independent of vendor or modality. PACS and telemedicine systems that support DICOM formats can then store, manipulate, and exchange images with all other medical devices and display workstations which support the same DICOM formats.

In this article, we discuss the design of multimedia systems for telemedicine. First, various applications of telemedicine are presented, and their multimedia and communications requirements discussed. A telemedicine prototype is then presented, each of its components discussed, and a potential future telemedicine system shown. This is followed by a section summarizing the general communication requirements of each multimedia bitstream common to telemedicine systems. Finally, integrated services digital network (ISDN) and asynchronous transfer mode (ATM) are compared as potential backbone technologies for telemedicine networks.

Applications

The communications needs of a multimedia system for telemedicine are largely dependent on the type of telemedicine being addressed. The types of telemedicine include teleconsultation, telediagnosis, and tele-education. Teleconsultation is the interactive sharing of images and medical information in which the primary diagnosis is made by the doctor at the location of the patient. The purpose of teleconsultation is to provide a "second opinion" by a remote specialist to confirm the diagnosis by the local physician or help the local physician in arriving at a correct diagnosis. In this case, video conferencing, including synchronized two-way audio and video, is important to support the verbal and nonverbal cues used in face-to-face conversation. As long as video is only used for conferencing, it does not need to be high-quality; however, audio should be clear and uninterrupted with little delay. Image quality should be good, although some loss in quality may be acceptable in teleconsultation.

One example of a teleconsultation system is the WAMI (Washington, Alaska, Montana, and Idaho) Rural Telemedicine Network [10]. One rural clinic in each of the

Application	Media requirements	Remote control
Teleradiology	Large images	None
Telepathology	Still images	Microscope, camera
Teledermatology	High-quality video or still images	Camera
Telecardiology	High-quality video	None
Tele-endoscopy	High-quality video	None
Telepsychiatry	Teleconferencing video	Camera

■ **Table 1.** *Telemedicine applications and their media and remote control requirements.*

four states has been equipped with two 56 kb/s frame relay connections and a personal computer (PC)-based teleconferencing system from PictureTel Corporation (Danvers, Massachusetts), including a digital speakerphone, a fax machine, a digital camera, an X-ray digitizer, and a monitor. With these systems, primary care physicians in the remote clinics can consult with specialists using a similar system located at the University of Washington Medical Center or one of the other major medical centers in Seattle. Currently, consultations are usually scheduled in advance depending on the availability of the specialists. Both users can see and speak to each other in real time as well as send images and other files to the remote site. They can also use a "white board" to view and annotate text or images simultaneously. Diagnostic-quality video (e.g., ultrasound) can be captured and compressed off-line, transferred to the remote site, and played back.

Telediagnosis is the sharing of images and medical information in which the primary diagnosis is made by a doctor at a location remote from the patient. The important distinction between teleconsultation and telediagnosis is that, with telediagnosis, there should be no significant loss of image quality by the telemedicine system in acquisition, compression, processing, transmission, and display. Telediagnostic systems can be either synchronous (interactive) or asynchronous. Synchronous telediagnosis has roughly the same video conferencing and document-sharing requirements as teleconsultation, but it takes a higher communications bandwidth in order to support interactive image transfer and real-time high-quality diagnostic video. Asynchronous telediagnosis is based on a "store-and-forward" architecture in which the images, video, audio, and text are assembled into a sort of "multimedia email" and delivered to the expert for diagnosis at his/her convenience. After the diagnosis is made, the results are delivered to the referring physician. If used infrequently, asynchronous telediagnosis could have lower bandwidth requirements than either synchronous telediagnosis or teleconsultation.

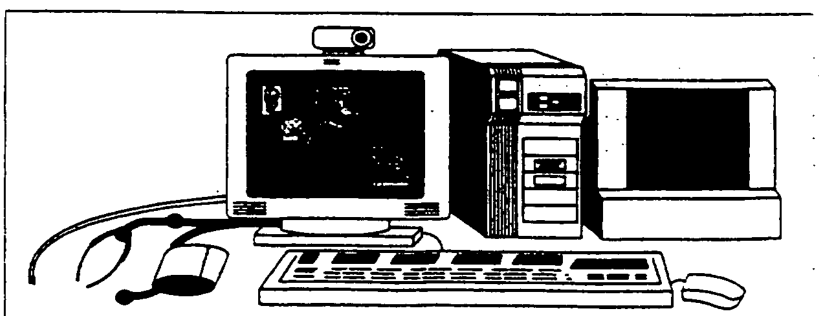
In trauma, telediagnosis can be used in an emergency situation in which a decision on whether or not to evacuate the patient needs to be made. For example, this was used in the Gulf War to determine whether a wounded soldier could be treated in the battlefield or should be evacuated to a hospital based on X-ray computed tomography (CT) images [11]. Similarly, trauma specialists can make a time-critical informed decision whether or not to transfer patients from the emergency room of a small remote hospital to a major trauma center. In both cases, fast access to images and other relevant information is essential.

Tele-education is the provision of educational materials over telecommunications networks. In terms of medical tele-education, this requires videoconferencing with document and image sharing capabilities. Depending on whether it is used for mentoring (one to one), on-line lecturing, or off-line continuing medical education, it may require either point-to-point or point-to-multipoint communications.

Telemedicine systems also vary by the application being supported, as shown in Table 1. Specific applications of telemedicine include teleradiology, telepathology, teledermatology, telecardiology, tele-endoscopy, and telepsychiatry. Teleradiology is telemedicine using medical images acquired from radiological modalities, which include X-ray, magnetic resonance (MR), CT, and nuclear medicine (NM), ultrasound, and others. The spatial and contrast (bits per pixel) resolutions of these images vary from modality to modality, but the most frequently used radiological images (X-rays) have high resolutions (typically 2048 x 2048 and higher) and depths (from 8-16 bits/pixel), and correspondingly large file sizes when stored digitally. In addition, MR, CT, and NM studies typically acquire a series of images which describe either a three-dimensional (3D) volume or a time-varying cross-section. Typical sizes of image stacks also vary by modality from 12 to 100 images/study. Therefore, the size of a typical large imaging study consisting of either 60 512 x 512 12-bit CT images or four 2048 x 2048 12-bit X-ray images would be approximately 250 Mb, assuming that each 12-bit pixel is stored in 2 bytes.

Telepathology is a form of telemedicine used by pathologists to examine tissues under a microscope. In some cases, pathologists examine tissues resected from a patient for signs of cancer while the patient is still anesthetized in an operating room to decide whether more resection is necessary. Using interactive telepathology, the pathologist can remotely control the microscope (focus, stage movement, magnification, and image capture) while observing the image obtained and transmitted from a camera attached to the microscope. In noninteractive telepathology, a low-power overview image and 10–20 of the 1000 possible high-power images of the slide are selected, captured via a microscope-mounted camera, and transferred to the remote pathologist for examination. Teledermatology resembles telepathology, except that it images the skin of a patient instead of a specimen under a microscope [12].

Telecardiology is the transmission of images of the heart using telemedicine. In ultrasound cardiology, a sonographer positions an ultrasound transducer near the patient's heart. The ultrasound machine processes the signals from the transducer in real time and outputs a dynamic image sequence of the heart at the video rate. In telecardiology, this video



■ **Figure 2.** *A future telemedicine system, including (from left to right) ATM interface, electronic stethoscope, digital blood pressure cuff, monitor with speakers, microphone and camera, keyboard and mouse, PC, and film digitizer.*

sequence is [illegible]
consultant, who views it in real time, directs the sonographer where to position the transducer, and makes a diagnosis.

An endoscope is a device used to produce images of structures inside the body. In tele-endoscopy, a doctor guides the endoscope to the location of interest. As with telecardiology, a remote specialist could view the video sequence from the endoscope in real time, direct the doctor controlling the endoscope, and make a diagnosis or offer an expert opinion.

Telepsychiatry is a form of telemedicine supporting the remote practice of psychiatry. This requires mainly video conferencing, including synchronized two-way audio and video with remotely controllable cameras.

TELEMEDICINE SYSTEMS

In order to gain first-hand experience with telemedicine and systematically analyze and collect its requirements, we have developed a prototypical telemedicine workstation [13]. Because of its flexibility and processing power, the MediaStation 5000 (MS5000) [14], which was designed and implemented by our team, has been used as the centerpiece of the workstation. The MS5000 is a single-board multimedia system capable of digitizing stereo audio and video, displaying up to 1280 x 1024 pixels, and performing image processing tasks requiring up to 2 billion operations/s, including real-time Motion Picture Experts Group 1 (MPEG-1) or H.320 compression and decompression, using the Texas Instruments TMS320C80 digital signal processor [15]. Coupled with an ATM network adapter, the system has been equipped to transmit and receive video, audio, and medical images. Because the MS5000 is programmable, it can also perform image display, image processing, and graphics functions such as window and level, unsharp masking, and 3D reconstruction.

Two telemedicine workstations were connected between the University of Washington and Madigan Army Medical Center (50 miles from the university) in January 1995 and demonstrated to a group of physicians from the University of Washington, Madigan Army Medical Center, and Seattle Veteran's Administration Hospital. A workstation, a Fore Systems (Warrendale, Pennsylvania) ASX-200 ATM switch and a DS-3 connection to a US West regional fiber ring supporting ATM over synchronous optical network (SONET) were installed at each site. X-ray, CT, and MR images were exchanged, manipulated, and discussed interactively between the two sites. Ultrasound video was acquired, compressed at one site, transmitted, decompressed, and displayed at the other site in real time using MPEG-1 at 30 frames per second (FPS). The general response from the physicians was positive, particularly with regard to the image quality, real-time MPEG video, and responsiveness of the system. Also, several areas for improvement were identified. Most significantly, the host central processing unit (CPU) (i486) and host buses (VL and EISA) of each workstation proved to be a bottleneck, limiting image transfer throughput to 13–15 Mb/s out of the 45 Mb/s DS-3 services.

The following requirements for a telemedicine system have been compiled based on this experience with telemedicine. Figure 2 illustrates a possible telemedicine workstation of the future which would be used in a remote location. This workstation would include an ATM interface, an electronic stethoscope, a digital blood pressure cuff, a monitor with speakers, a microphone and a camera, a PC, and a film digitizer. The corresponding system used by the consultant would be similar, but may not require media acquisition devices such as the film digitizer and stethoscope. Depending on a specific application, multimedia systems for telemedicine will require different combinations of the hardware and/or software components described under each of the following categories.

MEDIA ACQUISITION

Images may be obtained from a number of sources. Still digital cameras can be used for acquiring high-resolution images (e.g., for teledermatology or telepathology). X-ray films are digitized with laser scanners, while images from digital imaging modalities such as MR, CT, and CR are available directly in digital, DICOM-compliant formats.

Digital video may be either available directly (e.g., digital bitstreams from CD ROM, digital video disks, or next-generation ultrasound machines) or acquired through the combination of a video digitizer and an analog video source, such as a video camera, an ultrasound imager, or an endoscope. Audio may be obtained using an audio digitizer, while a digital stethoscope could provide another audio source.

MEDIA STORAGE

Video and audio clips and medical images require temporary or permanent local storage. This storage can be provided

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Multimedia streams	Description	Real-time?	Range of bitrates
System stream	Session connection/disconnection, mouse movements, synchronization	No	Negligible
Audio conferencing stream	Full duplex, G.72x audio	Yes	10–128 kb/s
Diagnostic audio stream	One-way, CD-quality, stereo audio	Yes	32–768 kb/s
Video conferencing stream	Two-way, H.261 video	Yes	64 kb/s–1.92 Mb/s
Diagnostic video stream	One-way, MPEG-2 video	Yes	3–15 Mb/s
Image transfer stream	Image transmission for consultation	No	7 Mb/s

■ **Table 2.** *Networking requirements of multimedia streams.*

through either magnetic and/or magneto-optical (MO) drives. If the telemedicine system is incorporated within a PACS as shown in Fig. 1, new incoming and old comparison images can be stored permanently in the PACS archive and accessed by the telemedicine system as needed.

Compression/Decompression

Compression of medical images has been historically reversible or "lossless," limiting compression ratios to between 2:1 and 4:1. Lossy compression schemes have not been widely used for both clinical and legal reasons. However, standard and newer compression algorithms such as Joint Photographic Experts Group (JPEG) and wavelet-based compression can yield "visually lossless" images with compression ratio between 10:1 and 20:1 [16, 17], which produce statistically identical diagnostic results compared with using the original images without any lossy compression. If this kind of compression is properly used and does not require much additional time for compression and decompression, it can significantly reduce the communications bandwidth, storage requirements, and overall delay in telemedicine systems.

The accepted international standard for videoconferencing is H.320 [18] which includes support for video (H.261) and audio (G.722, G.728) compression/decompression, multiplexing, and synchronization, as well as document sharing (T.120). H.320 is designed to work over the range of ISDN connections (from 64 kb/s to 1.92 Mb/s). There exist other compression standards which support higher-quality video and have correspondingly higher bandwidth requirements. Motion JPEG is a "symmetric" coder/decoder (codec) (it requires roughly the same amount of computation to encode and decode frames), which eliminates intraframe redundancy. Better compression ratios could be obtained by utilizing both interframe and intraframe redundancies. These algorithms require "asymmetric" codecs (which take significantly more computation to encode than to decode the frames due to motion estimation between successive video frames) such as MPEG-1 [19] or MPEG-2 [20]. MPEG-1 is mainly designed to compress video into a 1.2 Mb/s bitstream for VHS- or higher-quality video at higher bit rates. MPEG-2 is more flexible and supports various combinations of levels and profiles from VHS-quality up to high-definition television (HDTV)-quality video. At the main profile and main level, MPEG-2 can compress 720 x 480 video at 30 FPS into a 5–15 Mb/s bitstream [21].

Some compression can be accomplished in software, depending on the main CPU of the telemedicine system. For example, the public-domain MPEG decoder developed by MPEG Software Simulation Group achieves about 1 FPS on a PC with a 66 MHz Intel i486 processor and 1.4 FPS on a SparcStation 2 with an 80 MHz Weitek processor. On a high-end Sun SparcStation 20/71 that uses a three-issue superscalar processor running at 75 MHz, we have achieved about 5 FPS. To achieve the necessary image and video compression for telemedicine at real-time rates, a dedicated compression/ decompression board based on either programmable DSPs such as the Texas Instruments TMS320C8x family or special compression chipsets such as those from LSI Logic, C-Cube, or SGS-Thomson is normally required.

Image and Video Processing

Image processing requirements for telemedicine applications can be derived from duplicating the functionality available to corresponding tasks performed in the clinical environment without telemedicine. For example, radiologists and clinicians often have default orientations for images (e.g., the left portion of the image corresponds to the patient's left) which can vary between hospitals, departments, individuals, or imaging modalities. Basic image manipulation functions such as 90-degree rotations and horizontal and vertical flips are essential to correct the errors in image acquisition and ensure that images can be presented to the clinicians in the way in which they are accustomed to viewing them. This is particularly important in teleradiology. Zooming and panning are necessitated by the limited spatial resolution of cathode ray tubes (CRTs) when compared to X-ray films. Real-time window/level (brightness and contrast adjustment) is required by the need to interactively examine medical images with more than 8 b/pixel by adjusting the range (window) and the center position (level) in the wide input dynamic range [22]. In the case of diagnostic video, manipulation functions such as play, record, pause, and rewind are important for simulating the VCR environment often used in ultrasound consultation.

User Interface

The user interface should be graphical due to the fact that much of the information being shared in a telemedicine system is inherently graphical. One or more high-resolution displays, a keyboard, a pointing device such as a mouse, and a window manager such as Microsoft Windows make up a basic telemedicine user interface. These are all in addition to the multimedia devices (cameras, microphones, speakers) required by the application. In the future, a telemedicine interface needs to become "simpler." A single display, a single primary input device such as a reliable voice recognition unit for commands and report writing or a virtual reality glove, and automation of the most common tasks such as communications connection and disconnection and bandwidth allocation could significantly reduce the "information overload" of telemedicine interfaces and allow the user to focus on the tasks at hand.

Network Interfaces

Required network interfaces for telemedicine can range from low to high bandwidth, depending on the application. Low-bandwidth interfaces should support multiple links because low-bandwidth connections are often combined together to provide the bandwidth necessary for telemedicine. These interfaces include V.34 plain old telephone service (POTS) connections, 56 kb/s dedicated or frame relay connections, ISDN connections from 64 kb/s to 1.92 Mb/s, and fractional and full T1 interfaces which provide up to 1.54 Mb/s per con-

nection. Higher-bandwidth interfaces include TAXI (100 Mb/s) and SONET (155 Mb/s and higher). Furthermore, interfaces between the wide area network and local area networks (e.g., Ethernet, fiber distributed data interface, FDDI) will be required to allow the clinicians and other health care providers to access medical imaging devices, PACSs, and other medical information systems regardless of where they are located.

In a telemedicine system using special hardware for compression, it is highly desirable for the network interface to be tightly integrated with the compression hardware. This decreases network latency and reduces the processing load on the host. Bus mastering support by both the network interface and the compression hardware in a single-bus configuration could provide good performance, assuming other bus masters (including the host CPU) release control of the bus quickly. A better alternative would be to use a connection separate from the host bus, such as a second bus, or a high-speed serial connection, such as IEEE P1394 (Firewire) [23].

NETWORK PROTOCOLS

Support for standard networking protocols is critical to telemedicine systems in order to meet the performance and interoperability requirements. ATM [24] is the preferred internetworking protocol between telemedicine systems based on the bandwidth and quality of service requirements of medical video and imaging applications. Wide area networking connections at rates lower than T1 require ISDN or similar protocols. In locations where ISDN is not available, POTS could be used to support H.324 videoconferencing, a derivative of H.320 which includes support for communications at up to 64 kb/s. In addition, support for Transmission Control Protocol/Internet Protocol (TCP/IP) is most likely a requirement on both the LAN and WAN interfaces for access to medical records and other resources on remote local area networks.

Standards for supporting real-time audio and video services over most networking protocols, including ATM, are still being defined. Unlike H.320 (which was designed specifically for ISDN), most video compression methods have not been designed for a specific networking model. For instance, MPEG-2 depends on a constant channel delay to properly receive timing information [20]. ATM guarantees a maximum variance in delay, but not a constant delay. There is also a significant amount of redundancy in timing, multiplexing, and error detection and recovery information between the MPEG-2 transport stream and the ATM adaptation layer. The MPEG-2 quantization scale, which determines the compression ratio, does not automatically adjust to changes in the available network bandwidth. Therefore, although it is possible to carry MPEG-2 over ATM, the two standards are currently not well integrated. The ATM Forum is in the process of establishing a standard for better support of MPEG-2 over ATM [25]. Ways to guarantee a certain video or audio quality in the presence of congestion and other properties of real-world networks need to be investigated further.

COMMUNICATIONS REQUIREMENTS

The cumulative communications requirements of a telemedicine system vary from one application to another. The following discussion, summarized in Table 2, describes the general communication requirements of each bitstream common to telemedicine systems.

VIDEO

Telemedicine systems could require up to two or three simultaneous video bitstreams: two low-rate bitstreams for teleconferencing with an optional high-rate bitstream for diagnostic video. H.261 (64 kb/s to 1.92 Mb/s), H.263 (15–34 kb/s), or MPEG-1 (1.2–2 Mb/s) are suitable for each teleconferencing video stream, while better quality compression algorithms such as MPEG-1 or MPEG-2 at 3–15 Mb/s might be needed for the diagnostic video stream. In all cases, latency and jitter (the variance in the network arrival rate) of the real-time video streams are critical and should be minimized.

AUDIO

In addition to video, telemedicine systems require up to two or three simultaneous audio bitstreams: two low-rate bitstreams for teleconferencing, with an optional high-rate bitstream for diagnostic audio such as an electronic stethoscope or Doppler ultrasound audio. For example, a stethoscope from Andries Tek Inc. (Austin, Texas) can output good-quality digital audio at 128 kb/s using the Dolby AC-2 algorithm. Basic G.711 at 56 kb/s is noisy and considered unacceptable for medical consultation. However, G.722 (48–64 kb/s), G.723 (5–6 kb/s), G.726 (32 kb/s) and G.728 (16 kb/s) are more acceptable for teleconferencing. Diagnostic audio streams could require CD-quality audio such as MPEG-1 layer 2 audio

(32–256 kb/s) or Dolby AC-3 (96–768 kb/s). Teleconferencing audio needs to be synchronized with the video streams, and, as with video, latency and jitter of the real-time audio bitstreams should be minimized.

IMAGES

Images are generally transmitted unidirectionally, so a single image transfer stream is sufficient. Image transfers are high-volume (e.g., 10–250 Mb/transfer) and bursty (low mean transfer rate with high maximal transfer rates). Therefore, the image transfer stream could be normally disabled and enabled dynamically as needed. Bandwidth required is dependent on the types of images supported and the acceptable image delay. For example, a typical X-ray image is digitized at a resolution of 2048 x 2048 pixels and 12 b/pixel with each pixel stored in 2 bytes. If the maximum acceptable delay is 10 s/image, a bandwidth of at least 7 Mb/s would be required to transfer the image within this limit, ignoring network overhead and traffic. Unlike video and audio streams, latency is less critical to image transfers, and jitter is irrelevant.

MEDICAL RECORDS

Electronic medical record transfers are unidirectional transfers of principally text information. Text is compact and requires little bandwidth. Even an abnormally large patient record of 100 typewritten pages would represent only 3 Mb of uncompressed information. However, frequent additions of nontext information such as scanned handwritten records, electrocardiograms (ECGs), and other graphics records to the electronic patient record could significantly increase the size of the patient record and the required bandwidth. Medical records are also fairly static. Most of the medical records could be transferred prior to the telemedicine session. As with image transfers, bandwidth should be allocated to medical record transfer during a telemedicine session only as needed, latency is not critical, and jitter is irrelevant.

The power and attractiveness of telemedicine, health care market realignment, encouragement by various government agencies, decreasing costs of telecommunications and multimedia and further clinical experience will ultimately facilitate telemedicine's use and wide acceptance in the future.

TELEMEDICINE BACKBONE: ISDN OR ATM?

Given the previously described communication requirements, the question arises of which combination of technologies is best suited to a networking backbone for telemedicine. Most wide-area data networks today are routed networks which depend on routers to link the various local area networks. Routers work at a high level in the protocol hierarchy and exchange packets of information between networks of similar or different architecture fairly efficiently. However, routers are fundamentally shared network resources and do not provide guarantees in network bandwidth or quality of service. Switches, on the other hand, work at a lower level in the protocol stack and transfer packets or streams of information between similar networks far more efficiently. More important, switches are dedicated network resources and can guarantee network bandwidth and quality of service. Telemedicine's requirements on bandwidth, latency, and jitter make switch-based networks more suitable for telemedicine. Of the emerging switch-based wide area networking services, ISDN and ATM are the services best suited to telemedicine, excluding low-quality video conferencing such as H.324 over POTS. By comparison, frame relay uses variable-size packets which make it less suitable for real-time services, and switched multi-megabit data service (SMDS) offers reasonably high bandwidths (up to 155 Mb/s), but not the quality-of-service guarantees of ATM.

The bandwidth range of ISDN is from 64 kb/s (basic rate interface, BRI) to 1.92 Mb/s (primary rate interface, PRI), while ATM can support from 1.54 Mb/s (T1) to 2.4 Gb/s (OC-48) and beyond. The advantages of BRI ISDN are immediate availability in most areas, inexpensive telecommunications equipment and line rates, and greater protocol support among existing computing hardware and software [26]. However, bandwidth limitations confine video to two-way H.261 teleconferencing or one-way MPEG-1 at VHS quality even over PRI ISDN. Without compression, a large image transfer of 250 Mb over ISDN would require more than 2000 s at 128 kb/s or 130 s at 1.92 Mb/s, ignoring network overhead, during which no other operations could be performed. With 20:1 compression, this transfer would require 100 s at 128 kb/s or 6.5 s at 1.92 Mb/s, ignoring the time necessary to compress and decompress the images.

The advantages of ATM are higher bandwidths and statistical multiplexing of small packets (cells) with guaranteed bandwidth and minimal latency and jitter [27]. Unlike ISDN, the range of bandwidths supported by ATM is sufficient for the entire range of telemedicine applications, including MPEG-2 video streams. A large image transfer of 250 Mb would require 1.6 s at 155 Mb/s without compression, ignoring network overhead. With 20:1 compression and ignoring the time necessary to compress and decompress the images, this transfer would require only 0.08 s at 155 Mb/s. In addition, because ATM connections sharing physical links are logically separate, excess traffic from one connection would not impact other connections, including connections between the same source and destination. ATM also offers "bandwidth on demand," which allows a connection to deliver a higher bandwidth only when it is needed. The disadvantages of using ATM for telemedicine are the high costs and scarcity of ATM equipment and telecommunications lines, especially to rural areas. However, ATM equipment and line availability has been increasing steadily and is expected to improve considerably in the future, and costs are expected to decrease as the size of the ATM market and user acceptance increase. It should be noted that ATM is one of the technologies being evaluated by telecommunications and interactive television companies for providing video dial tone services to the home. Besides contributing to the ATM infrastructure, ATM to the home would have major implications for telemedicine, including emergency services, remote monitoring of vital signs, and home patient education, thus providing a communications infrastructure to realize an ultimate goal in telemedicine, the "electronic housecall."

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CONCLUSIONS

The networking requirements of telemedicine are application-specific. In most cases, telemedicine is much more than just teleconferencing. ISDN could be used in some low-end applications, but BRI ISDN does not provide the bandwidth necessary for a large number of telemedicine applications which require simultaneous multimedia bitstreams, especially diagnostic-quality, full-motion video. Many telemedicine applications would require the higher bandwidth and guaranteed qualities of service supported by ATM.

There are numerous technical and nontechnical challenges facing telemedicine. Telemedicine will grow slower than expected until several key issues, including cost effectiveness, are addressed and resolved. However, the power and attractiveness of telemedicine, health care market realignment, encouragement by various government agencies, decreasing costs of telecommunications and multimedia, and further clinical experience will ultimately facilitate telemedicine's use and wide acceptance in the future.

REFERENCES

[1] J. H. Sanders and R. L. Bashshur, "Challenges to the Implementation of Telemedicine," *Telemedicine J.*, vol. 1, no. 2, 1995, pp. 115-123.

[2] M. Moore, *Elements of Success in Telemedicine Projects*, Graduate School of Library and Information Science, University of Texas at Austin, 1993.

[3] C. L. Wittson, D. C. Affleck, and V. Johnson, *The Use of Two-Way Television in Group Therapy*, Nebraska Psychiatric Institute, University of Nebraska, Omaha, 1961.

[4] A. Jutra, "Teleroentgen Diagnosis by Means of Videotape Recording," *Am. J. Roentgenol.*, vol. 82, 1959, pp. 1099–1102.

[5] J. Grigsby and M. M. Kaehny, "Analysis of Expansion of Access to Care through Use of Telemedicine and Mobile Health Services, Report 1: Literature Review and Analytic Framework," Colorado Center for Health Policy Research, Denver, CO, 1993.

[6] D. A. Peredina and A. Allen, "Telemedicine Technology and Clinical Applications," *JAMA*, vol. 273, 1995, pp. 483–88.

[7] D. F. Leotta and Y. Kim, "Requirements for Picture Archiving and Communications Systems (PACS)," *IEEE EMB Mag.*, vol. 12, Mar. 1993, pp. 62–69.

[8] F. Goeringer, "Medical Diagnostic Imaging Support Systems for Military Medicine," *SPIE Medical Imaging IV: Image Capture, Formatting , and Display*, vol. 1444, 1991, pp. 340–50.

[9] American College of Radiology, National Electrical Manufacturers Association, "Digital Imaging and Communications in Medicine (DICOM): Version 3.0," Draft Standard, ACR-NEMA Committee, Working Group VI, Washington, DC, 1993.

[10] P. A. West, Private communication, Department of Family Medicine, University of Washington, Seattle, Aug. 1995.

[11] M. A. Cawthon *et al.*, "Preliminary Assessment of Computed Tomography and Satellite Teleradiology from Operation Desert Storm," *Invest. Radiol.*, vol. 26, 1991, pp. 854–57.

[12] D. C. Balch, "Telemedicine in Rural North Carolina," *Interactive Technology and the New Paradigm for Healthcare*, IOS Press, 1995, pp. 15–20.

[13] D. Parsons *et al.*, "MediaStation 5000: A Multimedia Workstation for Telemedicine," *SPIE Medical Imaging '95: Image Display*, vol. 2431, 1995, pp. 382–87.

[14] W. Lee *et al.*, "MediaStation 5000: Integrating Video and Audio," *IEEE Multimedia*, vol. 1, no. 2, 1994, pp. 50–61.

[15] K. Guttag, R. J. Gove, and J. R. Van Aken, "A Single-Chip Multiprocessor for Multimedia: The MVP," *IEEE Comp. Graphics & Apps.*, vol. 12, no. 6, 1992, pp. 53–64.

[16] H. Lee *et al.*, "A Predictive Classified Vector Quantizer and Its Subjective Quality Evaluation for X-ray CT Images," *IEEE Trans. on Medical Imaging*, vol. 14, 1995, pp. 397–406.

[17] H. MacMahon *et al.*, "Data Compression: Effect on Diagnostic Accuracy in Digital Chest Radiography," *Radiology*, vol. 178, 1991, pp. 175–79.

[18] ITU-T Rec. H.320, "Narrowband Visual Telephone Systems and Terminal Equipment," Rev. 1, Apr. 1994.

[19] MPEG-1 CD, Committee Draft ISO/IEC 11172 Working Group 11, ISO, IPSJ, Tokyo, Japan, Dec. 6, 1991.

[20] MPEG-2 CD, Committee Draft ISO/IEC 13818 JTC1/SC29/WG11, ITU, Mar. 25, 1994.

[21] D. Minoli, *Video Dialtone Technology*, New York: McGraw-Hill, 1995.

[22] W. Lee and Y. Kim, "Applications of a Multimedia System in Medical Imaging," *IEEE EMB Mag.*, vol. 15, no. 2, 1996, pp. 79–85.

[23] IEEE P1394/D7, "0.1v1 Draft of High Performance Serial Bus Core Requirements and Practices," IEEE, 1994.

[24] M. Kawarasaki and B. Jabbardi, "B-ISDN Architecture and Protocol," *IEEE JSAC*, vol. 9, no. 9, 1991, pp. 1405–15.

[25] ATM Forum, "Audiovisual Multimedia Services: Video on Demand Implementation Agreement 1.0," 1995.

[26] S. Akselsen, A. K. Eidsvik, and T. Fokow, "Telemedicine and ISDN," *IEEE Commun. Mag.*, vol. 31, no. 1, 1993, pp. 46–51.

[27] R. Handel, M. N. Huber, and S. Schroder, *ATM Networks: Concepts, Protocols, Applications*, Reading, MA: Addison-Wesley, 1993.

BIOGRAPHIES

JAMES E. CABRAL JR. is currently a Ph.D. student at the Image Computer Systems Laboratory in the Department of Electrical Engineering at the University of Washington. He earned an M.S.E.E. from the University of Washington in 1993 and a B.E. in electrical and biomedical engineering from Vanderbilt University in 1991. His current research interests are telemedicine, medical imaging, and ATM.

YONGMIN KIM received a B.S. in electronics engineering from Seoul National University, and the M.S.E.E. and Ph.D. from the University of Wisconsin, in 1975, 1979, and 1982, respectively. From 1982 to 1986, he was assistant professor of electrical engineering at the University of Washington, Seattle. From 1986 to 1990, he was associate professor of electrical engineering. Currently, he is professor of electrical engineering and adjunct professor of bioengineering, radiology, and computer science and engineering. Dr. Kim's current research interests include multimedia, image processing and computer graphics, medical imaging, telemedicine, PACS, and modeling and simulation. He has more than 240 research publications and many patents, and is the editor of eight Conference Proceedings. Dr. Kim and his research group have made many inventions in imaging and multimedia systems, transferring the invented technologies to industry with 12 licenses, and aided in the commercialization of these technologies. He has been a member (chairman, 1993–1994) of the Steering Committee of the *IEEE Transactions on Medical Imaging* since 1990, and is a member of the editorial boards of several journals. He is the director of both the Image Computing Systems Laboratory and the University of Washington Image Computing Library Consortium. Dr. Kim was awarded the 1988 Early Career Achievement Award of the IEEE/EMBS for his contributions to medical imaging. He is a fellow of the IEEE, the American Institute for Medical and Biological Engineering, and an ABET program evaluator for computer engineering.